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THE BOUNDARY LAYER AS A MEANS OF CONTROLLING THE FLOW OF LIQUIDS AND GASES

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Introduction

The phenomenon usually designated in hydrodynamics as the "boundary layer" occurs in flows with large Reynolds Numbers R** (1, 2, 3, 4).*** Physically, the form of flow with boundary layer is only a limiting case $(R \rightarrow \infty)$ of all possible forms of flow. Nevertheless, nearly all the forms of flow about aircraft, boats, and hydraulic machines belong to this group.

The "boundary layer" is the layer close to the boundary wall, in which the flow velocity drops rapidly from an external value, only slightly affected by the viscosity of the liquid,

*"Ueber die Beeinflüssung von Flüssigkeits- und Gasströmungen mit Hilfe der Grenzschicht" from Die Naturwissenschaften, Vol. 17, No. 34, August 23, 1929, pp. 663-670.

**R is $\frac{v l \rho}{\eta}$ where v is a velocity, ρ the density, and η the viscosity of the fluid, and l a longitudinal dimension of the installation which has to be determined in each individual case. The significance of R is explained by the Reynolds law of similarity often used in hydrodynamics, which reads as follows: Two flows about bodies arranged in a geometrically similar manner must be geometrically similar, when

$$R_1 = R_2, \text{ that is, } \frac{v_1 \, l_1 \, \rho_1}{\eta_1} = \frac{v_2 \, l_2 \, \rho_2}{\eta_2},$$

v_1 and v_2, l_1 and l_2 being pairs of values corresponding to the two flows.

***Numbers in parentheses refer to the bibliography at the end of the report.

to zero, measured with respect to the wall (Fig. 5). Unlike conditions in the external flow, there are considerable internal frictional forces in the boundary layer. Boundary layers have a thickness of about 0.1 to 1 cm for propeller blades, of 1 to 10 cm for airplane wings, and of 10 to 100 cm and more for airships and boats. Flows with small Reynolds Numbers differ from those with large numbers, in that the frictional effects due to the solid walls are not confined to thin layers, but penetrate far into the field of flow.

According to one of the main propositions of the boundary layer theory the scarcely noticeable boundary layer may, under certain conditions, have a decisive influence on the form of the external flow by causing it to separate from the wing surface. Even a layman may detect this separation by the formation of turbulent zones or regions sheltered from the wind. These phenomena are known to be caused by a kind of stagnation of the boundary layer at the point of separation (1, 3, 4, 18, 23, 24, 29, 30, 31). The present report deals with similar phenomena. It is important to note that usually the cause (external interference) directly affects only the layer close to the wall, while its indirect effect extends to a large portion of the external flow.

The Diffuser Principle

In order to reduce the drag of boats, rudders, propeller blades, airplane wings, fuselages, and airships, their rear portions are tapered. For the same reason, diffusers (funnel-shaped members of pipe systems) are given small diverging angles, so as to convert the greatest possible part of the kinetic energy into pressure and thus avoid greater energy losses.* This so fully agrees with the experimentally acquired "natural" feeling, that the actual reason for these often complicated shapes generally escapes notice. In a perfect potential flow (an imaginary flow without any boundary layer), in which the outermost particles do not adhere to the solid body but glide along without friction, thick bodies with untapered rear portions (excepting sharp-edged bodies) would encounter as little resistance as tapered bodies, and any type of diffuser would have an efficiency of 100%.

In reality, all these conditions are completely changed by the boundary layer. Boundary layers cannot overcome very great pressure increases. The tapering of lift and drag bodies, as well as of diffusers, is only intended to guide boundary layers along paths with small pressure increases. If a steep pressure gradient is required of a boundary layer, it "stagnates," owing to its reduced energy, and causes the separation of the

*Diffusers are conically shaped intermediate members connecting two pipes of different cross sections (Fig. 1).

whole flow from the surface of the body. Under these conditions the expected pressure increase, which is closely related to the velocity conditions in the whole field, does not take place or is adapted to the boundary layer.

As regards the danger of pressure increase, the relation between all the above-mentioned constructional shapes lies in the fact that any obstacle in a flow path causes first a reduction and then an enlargement of the flow cross section, the latter effect being important in this connection. The conversion of kinetic into potential energy, which is the actual function of a diffuser, must take place in the expanding zone. A lift-producing wing causes a greater pressure increase than an ordinary drag body, since good lift production requires strong negative pressure at the leading edge of the upper wing surface (whence "suction side"), this pressure having to be reduced again at the tapered trailing edge.

In this connection a variation of the angle of attack has the same effect as a variation of the diffuser angle. Also the wing, like the diffuser, has a limiting angle beyond which the required pressure increase is excessive. Beyond this angle the lifting power of the wing decreases considerably (Figs. 1 and 2). The pilot adapts himself to this peculiarity of the boundary layer by being careful not to stall his airplane.

Artificial Production of Turbulence in the Boundary Layer

The following experiment was made with a sphere of 200 mm diameter (5, 6, 7). The nondimensional coefficient obtained for drag, measured at a wind velocity of about 10 m/s, was

$$c_W = \frac{W}{\frac{\rho}{2} v^2 \ r^2 \ \pi} = 0.48.$$

When a ring, of slightly smaller diameter than the sphere and made of 0.2 to 1 mm wire, was placed on the front side of the sphere, parallel to the equator (the great circle perpendicular to the direction of flow), the drag was found to drop to approximately 0.15. The surprising fact that an apparent obstacle causes such a reduction in the drag is explained by the boundary layer phenomena.

Thus far no reference has been made to the fact that there are two types of boundary layers, the one with laminar and the other with turbulent flow (2, 3, 4, 5).* Laminar boundary layers are found at somewhat smaller Reynolds Numbers R. With increasing values of R, for example, with increasing velocity, they change (usually in a desultory manner) to turbulent layers, which are found almost exclusively at very large Reynolds Numbers. Under the turbulent boundary layer there is a very much thinner laminar layer.

*A laminar flow consists of smooth parallel fluid filaments; a turbulent flow of irregularly interwoven filaments.

There are close analogies between the behavior of the two types but, on the other hand, there are also marked differences. The two types differ particularly with respect to the transmission of power from layer to layer. In a laminar boundary layer, the tangential forces between adjacent parallel layers flowing at different velocities are determined only by the internal friction. In a turbulent boundary layer there is a lively exchange of fluid particles which transfer the momentum of their original layers to other layers, thus producing an apparent "internal friction" which is much greater than the actual friction. It follows from the greatly increased towing effect of the turbulent flow that, under the impetus of the free flow, turbulent boundary layers are capable of overcoming a much greater pressure increase than laminar layers without weakening and causing the separation of the whole flow.

While in the sub-critical region (i.e., within the R limits of the laminar boundary layer) the flow about a sphere separates near the equator, in the supercritical region it conforms for a certain distance (though with a thickened boundary layer) to the rear surface of the sphere, thus reducing the size of the vortical region and also the drag. Since, in the case of the sphere, a slightly greater velocity of approximately 15 m/s would cause the laminar boundary layer to change into a turbulent boundary layer without the use of a wire ring, it is obvious that the latter serves merely as a turbulence producer. A

similar effect is produced by a small wire stretched in front of the sphere.

These tests are of great theoretical importance, since they show the releasing or relaying effect of the boundary-layer flow. Its practical application has often been considered, on the one hand, for reducing the drag in certain favorable cases and, on the other hand, for obtaining as uniform a flow as possible with a turbulent boundary layer, over a wide range of Reynolds Numbers (for example, maintaining the constancy of the flow coefficients of Venturi tubes). Turbulent boundary layers are present from the beginning in most technical flow phenomena, so that their effect requires no further consideration.

Flow Unfavorably Affected by Roughness

As shown above, a turbulent boundary layer may improve the flow under certain conditions (i.e., cause the flow to approach the potential flow which conforms perfectly to the surface). In most other cases the flow is unfavorably affected by surface roughness.

With spheres almost every observer obtained different drag values. Their magnitude was found to depend largely on the method of suspension of the sphere. The best way was to mount the model on a strut secured at its rear stagnation point (7). The great influence of other systems of suspension is shown by the following test. If, in the case of a sphere of 20 cm diam-

eter correctly suspended at its rear stagnation point, two small wires of 0.8 mm diameter and 110 mm length are stuck into the surface near the equator, the total drag can be increased by over 100%, although the additional drag of the wire is negligible. This increase of drag is of course based on the assumption of previously existing turbulence. Phenomena not quite so striking but of greater technical importance, were observed on airfoils (8, 9). On the upper surface of a good wing model of 30 cm chord, a strip of wire gauze, 4 cm wide, was stretched over the whole span near the leading edge. The maximum elevation of the gauze was about 1 mm. The maximum lift was thus reduced from $c_a = 1.2$ to $c_a = 0.6$. At the same time the profile drag was increased, for the same angle of attack, to a multiple of its former value.

Unilateral impairment of the flow about a symmetrical body can also produce lift. This was shown by a test with a body of elliptical cross section (ratio of axes 2/5), the longer axis of which was placed in the direction of the air flow without any angle of attack (10). A 2-mm wire, stretched across the profile at a suitable point (where the slot shown in Fig. 3 had been provided for other tests) parallel to the cylinder axis, produced a lift $c_a = 0.4$, which corresponded approximately to the condition of lightly loaded and fast flying airplane wings. The boundary-layer thickness, without the wire, was also about 2 mm. This was due to the fact that, owing to a certain thick-

ening of the boundary layer on the disturbed side, the streamlines did not conform closely to the rounding of the profile, while those on the opposite undisturbed side adhered much better, because the opposition encountered at the rear end of the profile was greatly reduced and could be easily overcome. Thus an unsymmetrical lift-producing flow was developed about the profile.

Flow Unfavorably Affected by Expelled Air

The effect of small quantities of outflowing air is similar to that of roughness. The airplane designer accordingly avoids leaks in the upper surface of the wing. The above-mentioned method of producing lift about symmetrical bodies can also be employed with the substitution of a little expelled air instead of the wire (10). It has been found to be better to give the expelled air a direction opposite to that of the flow. This is accomplished by means of a slot as shown in Figure 3. Thus a lift coefficient $c_a = 0.4$ is obtained for the layers of expelled air which, reaching full speed without being mixed, have a thickness of 0.5% of the length of the longer axis of the ellipse. This is approximately half the amount of air originally contained in the boundary layer.

Another just-completed series of tests (suggested by Professor Betz) (11) deals with the means of preventing the so-called autorotation of airfoils. There is a close relation be-

tween autorotation and spinning, with which the public is now familiar through the exhibitions of stunt flyers and many accidents. The tendency to spin is an undesirable feature of many airplanes which even modern construction methods have often failed to eradicate completely.

Spinning results from the joint action of various aerodynamic and dynamic conditions. One of these is autorotation, which can be studied separately by means of the arrangement shown in Figure 4. An airfoil is attached to a rotatable spindle parallel to the air flow, the leading and trailing edges of the airfoil being perpendicular to the flow. The angle of attack can vary between 10 and 40°. In spite of the symmetry of this arrangement there are, for certain angles of attack, constant revolution speeds at which the wing rotates like a windmill without any external force.

According to the aforementioned tests, this phenomenon could be eliminated or at least reduced to 25-35% of its original value by providing the upper wing surface with two symmetrical internally connected slots (Fig. 4). Owing to the special aerodynamic-pressure conditions about a wing in autorotation, such an arrangement produces a flow through the slots. This flow is inward in the downward-moving half of the wing, and outward in the upward-moving half. The result of this process is a slight improvement, by suction, of the formerly detached external flow in the downward-moving half. On the other hand, the formerly

adhering flow at the other end is obviously very unfavorably affected by the expelled air. Under these conditions, the lift of the two wing portions changes so that the number of revolutions is greatly reduced.

Flow Improved by Expelled Air

Air flows are usually found to be unfavorably affected by expelled air. In one case, however, conditions are reversed and separation is prevented. This occurs when an air layer is strongly expelled in the direction of flow and thus imparts a new forward impulse to a flagging boundary layer.* This is shown graphically in Figures 5a and b. Separation takes place in Figure 5a (reversion of the direction of flow being equivalent to separation). It is avoided in Figure 5b. The process takes place in a retarded flow with pressure increase.

Up to now this idea has found no technical application. Although tests were made in different laboratories (12, 13), as well as the Göttingen investigations** under Professor Baumann, the outflow efficiency hitherto measured was too great to use in practice. This failure, however, is not due to the inadequacy of the principle, but to the exceptional difficulties of such tests. Good results may be obtained by going further into the matter.

*Patent of the late Professor A. Baumann in Stuttgart.
**Publication of which is pending (R. Langer, editor).

During the tests it was sought to raise the upper limit of useful angles of attack of the wing section, thus reducing the danger of stalling. An upward extension of the range of the angles of attack is important, particularly for taking off and landing, because the lifting power of the airplane must then be maintained at the lowest possible speed.

Thus the wing in Figure 6 (chord 200 mm, width of slot 5 mm) has a maximum lift coefficient $c_a = 1.95$, as against 1.27 for a smooth wing section without expelling air. In this case the velocity of the expelled air was approximately twice the velocity of the external air, and the internal pressure was three times the impact pressure of the external air. By further increasing the velocity of the expelled air, the maximum c_a value could be increased far beyond 2.

Slotted Wing (14-21)

Three types of slotted wings are shown in Figure 7. The total area of these wing sections is divided by one or more slots through which, during flight, the air flows in the direction of the arrows. Obviously the effect must be similar to that of a wing from which the boundary layer is removed by blowing, without, however, requiring the use of a pump. In certain cases, slots increase the lift of an ordinary wing as much as 50%. This advantage is not gained, however, without some disadvantages. For small c_a values, such as can be obtained without

slots, the drag of a slotted wing is much greater than that of a plain wing. The Handley Page wing avoids this result by the use of a slot similar to that of Figure 7a. This slot is opened only at large angles of attack, when the small front wing separates automatically from the main wing. The slot remains closed at small angles of attack, and the wing has approximately the aerodynamic characteristics of a plain wing.

The principle of the slotted wing has been applied in airplane construction for many years and particularly, in the form of the Handley Page wing. It has not, however, found universal approval, perhaps chiefly because aircraft designers fear the failure of the rather complicated opening device.

An explanation of the action of the slotted wing can be deduced from Figure 5b. In this case, however, the air is not expelled from the inside of the wing but through the slot from the lower side of the wing. The only difference is that, according to a simple consideration (Bernoulli's law), the velocity of the introduced air cannot be greater than the prevailing velocity outside the boundary layer. Under these conditions momentum in any desired amount cannot be imparted to the boundary layer through a single slot.

Removal of Boundary Layer by Suction (1, 3, 4, 22-25)

There is still another means of preventing separation by simply removing the retarded layer in the neighborhood of the wall. This result is achieved by sucking the layer into the inside of the body (Fig. 5c). Prandtl indicated the principle of boundary-layer removal by suction in 1904, in his first lecture on the boundary-layer theory (1). He confirmed his statements by a most convincing suction test. Later there arose the idea of a technical application of this principle (2, 23).

In this connection it was found that a considerable amount of experimental work was still necessary in order to obtain useful results. Only part of this work has yet been done. During the past few years several series of tests with very thick wing sections were carried out for the purpose of devising some means for producing great lift with the smallest possible suction volume. In checking the suction volumes measured for given lift values (as, for example, a lift coefficient $c_a = 2.7$),* the following figures are obtained:

Year	1924-25	1925	1927	1929
c_Q	0.05	0.024	0.020	0.014

c_Q is a nondimensional quantity coefficient proportional to the suction volume.** The first three numbers are taken from an

*Approximately twice the maximum value attainable with ordinary wings without suction (Fig. 2).

**$Q = c_Q\, v\, F$ is the suction volume for a wind velocity v and a wing area F.

earlier publication (25), the latter from incompleted tests by the writer. There are reasons to believe that even the last value is not a minimum. The difficulties are due partly to the test methods, which require gradual development, and partly to the great variety of possible variations, which can affect the final result and render any systematic investigations almost impossible. It is especially important to determine how closely the actual suction volume approaches the theoretically sufficient minimum value, and why greater volumes have hitherto been required. It may be assumed at first that separation can be prevented by drawing off the boundary-layer stratum closest to the wall. It has the smallest amount of energy and, as previously mentioned, always has a laminar form of flow. It is hoped that pending tests will solve this problem. In addition to the airfoil tests, investigations were also carried out for the purpose of improving the efficiency of diffusers or reducing their length (greater diverging angle). A few tests were also made for the purpose of reducing the drag (23, 24). Combinations of different effects described in this report may find useful applications. Tests are also contemplated in this connection.

The Magnus Effect (26-31)

Several years ago the construction of the first rotor ship aroused general interest in the Magnus effect on rotating cylinders (28-31). Therefore we need only recall that the rotation

retards the separation on the side of the cylinder moving with the wind but hastens it on the side moving against the wind, thus producing an unsymmetrical, lift-producing, resultant flow.

It is important to note that the rotation of the cylinder affects only the "relay" or boundary layer of the air flow, which in turn controls the external flow in such a manner that it produces an aerodynamic force with a component in the desired direction. There is no direct connection between the power used to produce the rotation and the propelling power of a rotor-driven craft.

Early attempts to explain the Magnus effect by the direct action of rotation on the whole field, without the intermediation of the boundary layer, failed to give quantitatively useful results. It is not quite clear how direct friction and any possibly related mixture influence can so greatly disturb the symmetry of the whole velocity field as to account for the production of the "lift" or forward thrust. Even in still air, the cylinder is able to impart a noticeable rotation to only a very thin layer along its own surface. To conclude according to the magnitude of the attainable lift, the fact that the velocity of the external air flow along the greater portion of the side of the cylinder moving with the wind exceeds the peripheral velocity of the cylinder, shows that the air is not swept along by the cylinder.

The application of the rotor principle to the propulsion

of boats seems to have reached a stagnation point, chiefly because the use of wind-driven ships in general is decreasing. Moreover, the equipment and running expenses of the first rotor ships have hitherto failed to enable them to compete with power-driven craft. Their development is also hampered by the fact that the construction of a rotor ship is rather expensive and nobody wants to make the experiment on a large scale with the risk of failure.

Tests for the purpose of attaining very high lift coefficients were recently made in Göttingen.* c_a values up to 16.5 for a ratio $\frac{u}{v} = 13$ (u being the peripheral velocity of the body and v the wind velocity) were reached with cylinders having a ratio of diameter to length of 1 : 12 and with large end disks.

Attention has been called frequently to the Magnus effect in ball playing (tennis, cricket). A ball, to which great velocity and simultaneous strong spiral motion are imparted, can be to a considerable extent, vertically or horizontally deflected from its normal trajectory. The tennis player knows this and "cuts" the ball, while the cricket player strikes it excentrically. For the purpose of getting better acquainted with these forces the writer has made a few tests with a rotating sphere. The sphere, 20 cm in diameter, was suspended in the 1.2 meter

*To appear in the 1930 issue (Report IV) of the Ergebnisse der Aerodynamischen Versuchsanstalt (edited by A. Busemann).

wind tunnel on a small wire which was rotated at its upper end. The reaction or backward force (drag) and the force transverse to the flow (lift) were determined from the inclination of the wire. The Reynolds Numbers adopted for these tests were roughly those of the motion of tennis and cricket balls. The test apparatus was very simple and could not give very accurate results, but the order of magnitude of the effect is clearly shown in the diagram of the results.* The $\frac{u}{v}$ values in the ball plays can be estimated. According to a consideration of the momentum and rotational force the value of $\frac{u}{v}$ varies between 0 and about 1.5. Thus, for a flight velocity of 22 m/s, a spiral force of $\frac{u}{v} = 0.8$ produces a lift of

$$A = c_a \frac{\rho}{2} v^2 R^2 \pi$$

$$\approx 0.28 \times \frac{1}{16} \times 484 \times 0.0033 \approx 0.028 \text{ kg}$$

This is about half the weight of a tennis ball. For $\frac{u}{v} = 0.2$ and $c_a = 0.19$ the value is about 0.019 kg. Thus, for the assumed velocity, we can obtain an additional curvature of the trajectory of the ball equal to 1/2 or 1/3 of the normal trajectory under the action of gravity alone.

All the above methods of flow control are based on the use of the boundary layer as a relay for controlling a larger region of flow. In this respect, they are theoretically related and

*It is proposed to make more accurate measurements (by weighing the forces) with less primitive apparatus. Similar measurements under somewhat different test conditions have also been made in England.

constitute a comprehensive amount of data and evidence on the theory of fluid motion with decreasing friction (boundary-layer theory) (1). Some of these methods have been adopted in practice. After certain initial difficulties have been overcome, other methods, which are now only of theoretical interest, may also be made to serve practical purposes.

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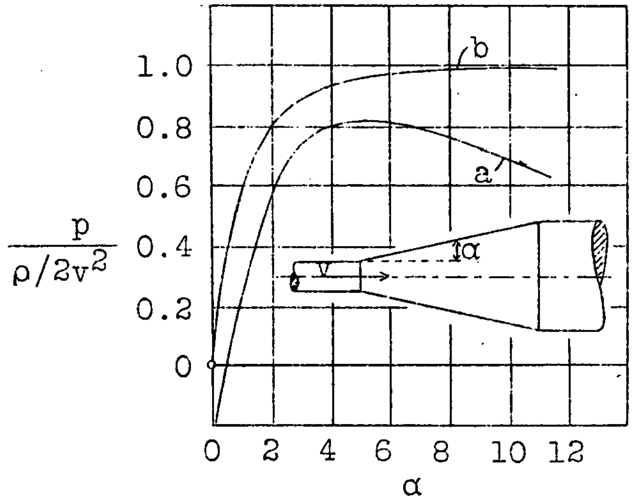

Fig.1 Pressure gain p in a diffuser plotted against the angle of divergence α for a constant length of the diffuser. The pressure gain p is expressed as a function of the kinetic energy $\frac{\rho}{2}v^2$ (impact pressure) available per unit volume. a, denotes the actual pressure gain and b, the gain anticipated according to the frictionless theory (ideal flow). The diffuser efficiency η equals the actual value divided by the theoretical value.

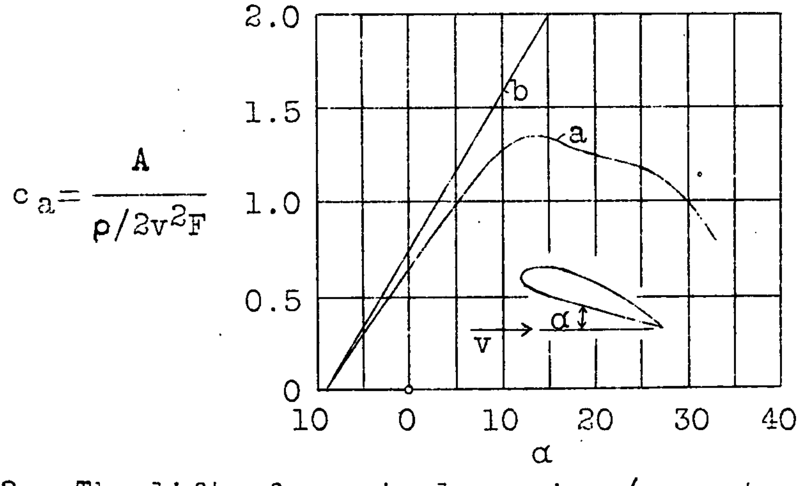

Fig.2 The lift of an airplane wing (aspect ratio 5) plotted against the angle of attack. As usual the lift **A** is referred to the impact pressure $\frac{\rho}{2}v^2$ of the air flow and to the wing area F. a, is the actual lift curve and b, the curve for frictionless flow.

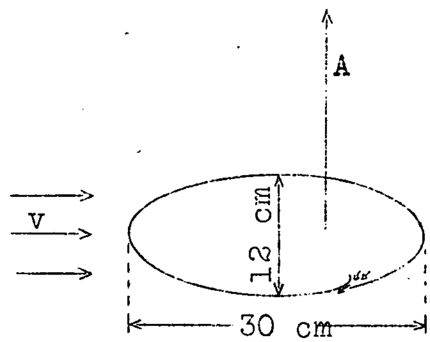

Fig.3 Air-expulsion arrangement for lift production on a symmetrical elliptic body (A = lift.)

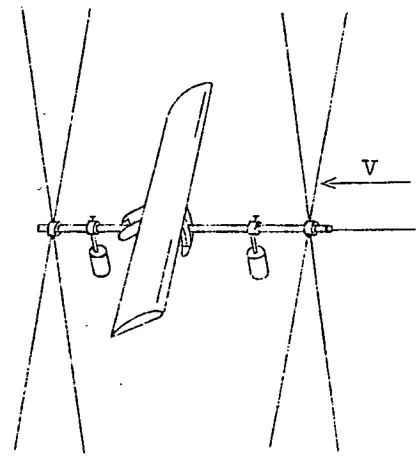

Fig.4 Arrangement for airfoil autorotation tests. The longitudinal wing slots serve to check autorotation and the weights to balance the airfoil about its C.G.

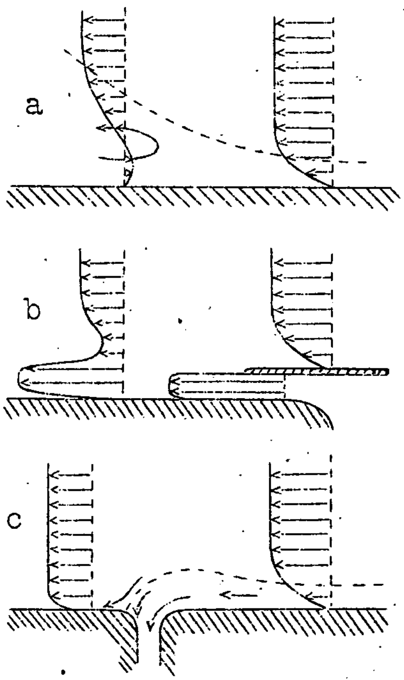

Fig.5 Development of a boundary layer in a region with strong pressure increase along the surface of the body (Boundary layer thickness exaggerated).

a, Without special precautions (separation),

b, Separation delayed by blowing,

c, Separation delayed by suction,

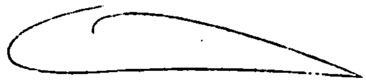

Fig.6 Wing from which the boundary layer is removed by blowing.

a

b

c

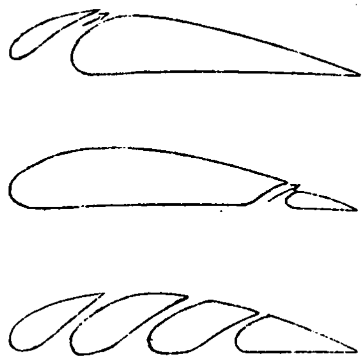

Fig.7 Slotted wings.

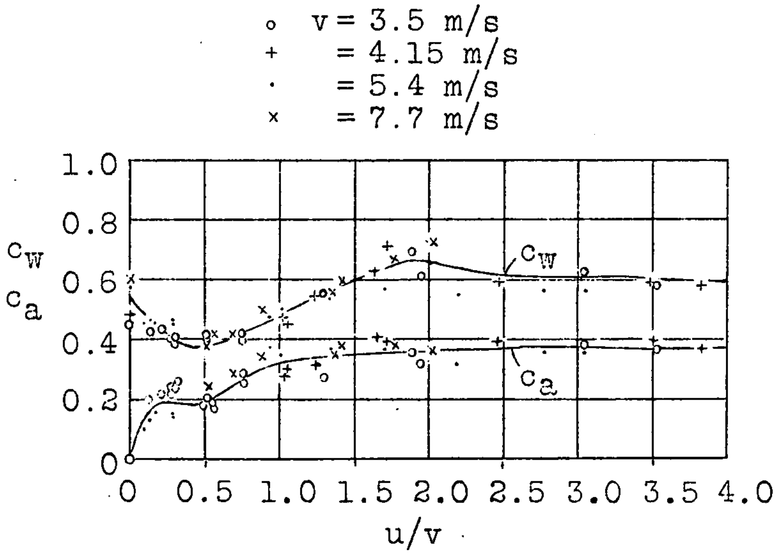

Fig.8 Experimental determination of the Magnus effect with a rotating sphere, u, being the peripheral velocity of the sphere, v, the wind velocity, $c_a = \frac{A}{\rho/2\ v^2\ R^2\ \pi}$ the non-dimensional coefficient of lift (transverse force) and $c_w = \frac{W}{\rho/2\ v^2\ r^2\ \pi}$ the coefficient of drag (backward force).